SO(10): A possible scenario for new physics in the neutrino sector and baryogenesis

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The implications on neutrino physics and on the dynamical generation of the baryonic asymmetry of a class of $SO(10)$ non-supersymmetric models are discussed.

1. INTRODUCTION

In the last years $SO(10)$ non-supersymmetric GUT models [1] have been the subject of renewed attention because people recognized they may represent a Standard Model (SM) extension in which the unification of the strong, electromagnetic and weak interactions is consistent with the experimental values of $\alpha(M_Z)$, $\sin^2\theta_W(M_Z)$ and $\alpha_S(M_Z)$. Moreover, they can give, through the see-saw mechanism [2], neutrino masses of the order required to explain the solar-neutrino problem within the framework of the MSW theory [3], and to account for the baryon asymmetry [4] and for at least part of the dark matter of the universe [5].

In this paper we will describe the results of a research on four particular $SO(10)$ symmetry breaking patterns. By studying the Higgs potential of the model, and using the Renormalization Group Equations (RGE), it was possible to deduce [6] the values of the two physical scales of the theory: the unification scale, M_X, at which $SO(10)$ breaks to an intermediate group G' (in the cases under investigation always greater than the standard group, $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \equiv G_{SM}$), and the intermediate scale, M_R, at which the intermediate group is broken to the standard group, G_{SM}. Therefore, a typical $SO(10)$ breaking chain is given by

$$SO(10) \xrightarrow{M_X} G' \xrightarrow{M_R} G_{SM} \xrightarrow{M_Z} SU(3)_c \otimes U(1)_Q. \quad (1)$$

M_X is connected with the masses of the lepto-quarks which mediate proton decay, and, in particular, the present experimental lower limit on proton decay, $\tau_{p\to e^+\pi^0} \geq 9 \cdot 10^{32} \ years$ [7], corresponds [8] to the following lower limit on M_X:

$$M_X \geq 3.2 \cdot 10^{15} \ GeV. \quad (2)$$

Through the see-saw mechanism, M_R is related to the masses of the (almost) left-handed neutrinos.

2. $SO(10)$ GUT MODELS

$SO(10)$ unified models have been studied since many years with the physical motivation of obtaining values for the masses of the lepto-quarks which mediate proton decay higher than the ones found within the $SU(5)$ minimal model.

Recently, the more precise determination of the gauge coupling constants at the scale M_Z has allowed to show that, if only standard model particles contribute to the RGE, the three running coupling constants of G_{SM} meet at three different points [9] and only the meeting point of $\alpha_2(\mu)$ and $\alpha_S(\mu)$ corresponds to a value of the scale μ sufficiently high to comply with the experimental lower limit on proton decay.

$SO(10)$, in which the hypercharge is the combination of two generators belonging to its Cartan,

$$Y = T_{3R} + \frac{B-L}{2}, \quad (3)$$

where T_{3R} and $B-L$ belong to $SU(2)_R$ and

$SU(4)_{PS}$ respectively, is very promising to modify the SU(5) predictions in such a way to prevent conflict with experiment. In fact, if there is an intermediate symmetry group G' containing $SU(2)_R$ and/or $SU(4)_{PS}$, it is possible to substitute the Abelian evolution of Y with the non-Abelian one of either component of Y, getting a higher unification point.

$SO(10)$ also reduces more than $SU(5)$ the amount of arbitrariness which characterizes the SM. First of all, it accommodates in one irreducible representation (IR), the spinorial one of dimension 16, the 15 known left-handed fermions of a generation plus a new particle, whose quantum numbers are the same as those of the not yet discovered ν_L^c. In this way, a real unification is realized with respect to the reducible representation $\bar{5} + 10$ which accommodates the fermions in the minimal $SU(5)$. Moreover, the presence of ν_L^c leads to a mass matrix, for one generation of neutrinos, of the form

$$\begin{pmatrix} \overline{\nu_R^c} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & \frac{m_D}{2} \\ \frac{m_D}{2} & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_L^c \end{pmatrix} + \ h.c., \quad (4)$$

where m_D is the Dirac mass and M the Majorana mass of the right-handed neutrinos. If $m_D \ll M$, the hypothesis on which the see-saw mechanism relies, the diagonalization of the mass matrix in Eq. (4) gives the two eigenvalues

$$m_{\nu_1} \sim \frac{m_D^2}{M}, \quad m_{\nu_2} \sim M, \quad (5)$$

and the relation $m_{\nu_1} \ll m_D$ agrees with the observation that the neutrinos have a mass, if any, much smaller than the one of the other fermions.

Another well known feature implied by the choice of $SO(10)$ as a gauge group is the absence of triangle anomalies, due to the fact that in $SO(10)$ it is not possible to construct a cubic invariant with the adjoint representation which the gauge bosons belong to (In $SU(5)$ this results from an accidental cancellation of the $\bar{5}$ and 10 contributions.).

3. THE SPONTANEOUS SYMMETRY BREAKING OF $SO(10)$

In order to identify the possible directions for the Spontaneous Symmetry Breaking (SSB) of

Table 1
Classification of the Higgs G_{SM}-invariant components in the lower irreducible representation of $SO(10)$. G_{SM} is the standard group.

IR	G_{SM} -singlet	Symmetry
16	$\hat{\chi}$	$SU(5)$
45	$\hat{\alpha_1}$	$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \times D$
45	$\hat{\alpha_2}$	$SU(4)_{PS} \otimes SU(2)_L \otimes U(1)_{T_{3R}}$
54	$\hat{\sigma}$	$SU(4)_{PS} \otimes SU(2)_L \otimes SU(2)_R \times D$
126	$\hat{\psi}$	$SU(5)$
144	$\hat{\omega}$	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
210	$\hat{\phi_1}$	$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \times D$
210	$\hat{\phi_2}$	$SU(4)_{PS} \otimes SU(2)_L \otimes SU(2)_R$
210	$\hat{\phi_3}$	$SU(3)_c \otimes SU(2)_L \otimes U(1)_{T_{3R}} \otimes U(1)_{B-L}$

$SO(10)$, one has to classify the components, in the smallest IR's of the group, that are invariant under G_{SM}. From the classification in Table 1, where D stands for the left-right discrete symmetry which interchanges $SU(2)_L$ and $SU(2)_R$ [10], it is possible to understand the reason why the $SO(10)$ breaking chain typically has one more step than the $SU(5)$ one: indeed, we see that for all the IR's, but the 144, the little group of the G_{SM}-singlet is greater than G_{SM}.

Actually, either for phenomenological or for technical reasons, some of the directions in Table 1 cannot be used for the first spontaneous breaking step. The use of the 16, 126 and 144 representations would lead to the result that, like in $SU(5)$ GUT's, the three SM running coupling constants do not meet at the same point. Concerning the 45 representation, one can show that the only non-trivial positive definite invariant with degree ≤ 4 (as necessary in order to have a renormalizable potential) that one can build has its minimum in the $SU(5) \otimes U(1)$-invariant and its maximum in the $SO(8) \otimes SO(2)$-invariant directions [11], so that it is not possible to construct a Higgs potential with minimum along the $\hat{\alpha_1}$ or $\hat{\alpha_2}$ directions. Moreover, the $\hat{\phi_3}$ component in the 210 representation corresponds to a direction with neither $SU(4)_{PS}$ nor $SU(2)_R$ in the little group.

The previous considerations lead us to the fol-

lowing four patterns, in which the first steps are:

$SO(10)$

$(i) \xrightarrow{\hat{\sigma}} \quad SU(4)_{PS} \otimes SU(2)_L \otimes SU(2)_R \times D$

$(ii) \xrightarrow{\hat{\phi}_1} \quad SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \times D$

$(iii) \xrightarrow{\hat{\phi}_2} \quad SU(4)_{PS} \otimes SU(2)_L \otimes SU(2)_R$

$(iv) \xrightarrow{\hat{\phi}_4} \quad SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L},$

where $\hat{\phi}_4 = cos\theta\hat{\phi}_1 + sin\theta\hat{\phi}_2$.

The other steps of the SSB (see Eq. (1)) are common to the four patterns. The second one is realized using the $\hat{\psi}$-component of a $126 \oplus \overline{126}$ representation, and the third one by a combination of the $SU(3)_c \otimes U(1)_Q$-invariant components of two 10's, in such a way to avoid the unwanted relation $m_t = m_b$ [6].

The previous four possibilities have been studied in the Refs.[12–15][1]. In most of these papers the models have been investigated within the Extended Survival Hypothesis (ESH), which assumes that the Higgs scalars acquire their masses at the highest possible scale whenever this is not forbidden by symmetries [16]. However, as discussed in Ref.[6], the ESH may be too drastic since in the 210 and 126 representations of $SO(10)$ there are multiplets with high quantum numbers, which may give important contributions to the RGE. On the opposite side, if one assumes total freedom [17] in assigning masses to the Higgs scalars, huge uncertainties are introduced in the $SO(10)$-predictions. However, this assumption of total freedom is also too drastic; in fact, the mass spectrum of the Higgs scalars depends on the coefficients of the non-trivial invariants that appear in the scalar potential, which are constrained by the condition that the absolute minimum of the potential is in the direction giving the desired symmetry breaking pattern [6]. In Ref.[6], we released the ESH, but, by taking into account the just mentioned constraints on the Higgs spectra, we were able to derive some restrictive conditions on the contributions of the Higgs

scalars to the RGE, and showed that the resulting uncertainties on the $SO(10)$-predictions are much smaller than the ones expected by Ref.[17]. Then, for each of the four models under investigation, we searched for the upper limit on the intermediate scale, M_R^{UP}, corresponding to a lower limit on the neutrino masses, and evaluated the corresponding value of the unification scale, M_X [6].

We report here only the results for the case $G' = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$, which is the most interesting one:

$$M_R^{UP} = 1.2 \cdot 2.5^{0\pm1} \cdot 10^{11} \ GeV,$$

$$M_X = 1.9 \cdot 2.0^{0\pm1} \cdot 10^{16} \ GeV. \tag{6}$$

Within the see-saw mechanism, the upper limit for M_R gives rise to the following inequalities for m_{ν_τ} and m_{ν_μ}:

$$m_{\nu_\tau} \geq 11 \frac{g_{2R}(M_R)}{f_3(M_R)} \left(\frac{m_t}{100 \ GeV}\right)^2 \ eV$$

$$m_{\nu_\mu} \geq 2.4 \cdot 10^{-3} \frac{g_{2R}(M_R)}{f_2(M_R)} \ eV, \tag{7}$$

where g_{2R} and f_i are the $SU(2)_R$ gauge coupling constant and the Yukawa coupling of the $126 \oplus \overline{126}$ to the i-th family respectively. For natural values of g_{2R} and f_i, Eqs. (7) imply a substantial contribution of ν_τ to the dark matter in the universe and a m_{ν_μ} relevant for the MSW solution of the solar-neutrino problem.

4. $SO(10)$ BARYOGENESIS

Another interesting possible prediction of this class of $SO(10)$ models is a dynamical explanation of the presently observed baryon asymmetry. Indeed, these models can satisfy the three necessary conditions stated by Sakharov [18]: i) the $SO(10)$-gauge bosons mediate interactions which may lead to B-violations; ii) at the intermediate scale, C and CP symmetry are broken[2]; iii) non-equilibrium conditions can be implemented if the masses of the Higgs particles satisfy certain conditions.

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[1]Specifically, (i) has been analyzed in Ref.[12], (ii) in Ref.[13], (iii) in Ref.[14], and (iv) in Ref.[15].

[2]No ΔB can be generated until C and CP symmetry remain unbroken, and this happens only at M_R since the intermediate group has the same rank of $SO(10)$ [4].

A scenario in which i), ii), and iii) are realized is discussed in Ref.[4], in which our $SO(10)$ model with $G' = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ is considered. A non-zero value of $\Delta(B-L)$ is produced at $T \lesssim M_R$ by the $B - L$-violating decays $\tilde{\phi} \to \tilde{\psi} f \nu_L^c$, where $\tilde{\phi}$ are some Higgs multiplets of the 210 described in Ref.[4], $\tilde{\psi}$ are the Higgs of the 126 which have mass of order M_R, and f is a fermion. The knowledge of the mass spectrum of the Higgs scalars allowed the authors of Ref.[4] to verify the possibility to have an overabundant population of $\tilde{\phi}$ at M_R, expressed by the inequalities $10^{12} GeV \leq m_{\tilde{\phi}} \leq 4 \cdot 10^{14} GeV$, where the first and second inequality correspond to the condition that the annihilation and decay processes respectively are "frozen out". If no $B - L$-violating phenomena is active at lower temperatures, the stored $\Delta(B - L)$ is transformed in ΔB by the sphaleronic processes[3].

5. CONCLUSIONS

We find that $SO(10)$ phenomenology can quite naturally accomodate non-conventional neutrino physics and a dynamical mechanism for the generation of the baryonic asymmetry, and therefore these models may play an important role in future developments of astroparticle physics.

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[3]Note that the problem of the first proposals of $SO(10)$-based baryogenesis was that the sphaleronic processes would wash out the stored ΔB, but in the $SO(10)$-based baryogenesis here considered the sphaleronic processes play the positive role of transforming the stored $\Delta(B - L)$ in ΔB.